

Development of Linear Phase Modulator for Spacecraft Transponding Modem¹

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Abstract — A new Spacecraft Transponding Modem (STM) is being developed by the Jet Propulsion Laboratory for National Aeronautics and Space Administration (NASA) for deep space communication applications. The STM receives an X-band (7.17 GHz) uplink signal and generates an X-band (8.4 GHz) and a Ka-band (32.0 GHz) coherent or noncoherent downlink signals.

The STM architecture incorporates two miniature linear phase modulators. These modulators are used to modulate the X-band and Ka-band downlink frequencies with the downlink telemetry, turnaround ranging, or regenerative PN ranging signals.

The linear phase modulators are designed with custom developed microwave monolithic integrated circuit (MMIC) chips. The phase modulator MMICs, the amplifiers, and driver circuits are laid out on drop-in alumina substrates. These modulator designs meet the following requirements: phase deviation range of ± 140 degrees at X-band and Ka-band downlink carrier frequencies, phase linearity of less than 8%, phase modulation input bandwidth of greater than 100 MHz, and differential input with sinewave or squarewave modulating format.

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1. INTRODUCTION

This article summarizes the performance results of two hybrid linear-phase modulators developed for deep space Spacecraft Transponding Modem [1] application. The linear-phase modulators are used in the X-band synthesizer and the Ka-band synthesizer [1, 2] as shown in Figure 1.

Summary of Spacecraft Transponding Modem

The Spacecraft Transponding Modem implements the standard transponder functions and some of the command and telemetry channel service functions that have previously resided in spacecraft Command and Data Subsystem (CDS). The STM uses custom application specific integrated circuits (ASICs), MMICs, and multi chip module (MCM) packaging to reduce the active device parts count to 70, mass to 1.5 kg, and volume to 524 cm³.

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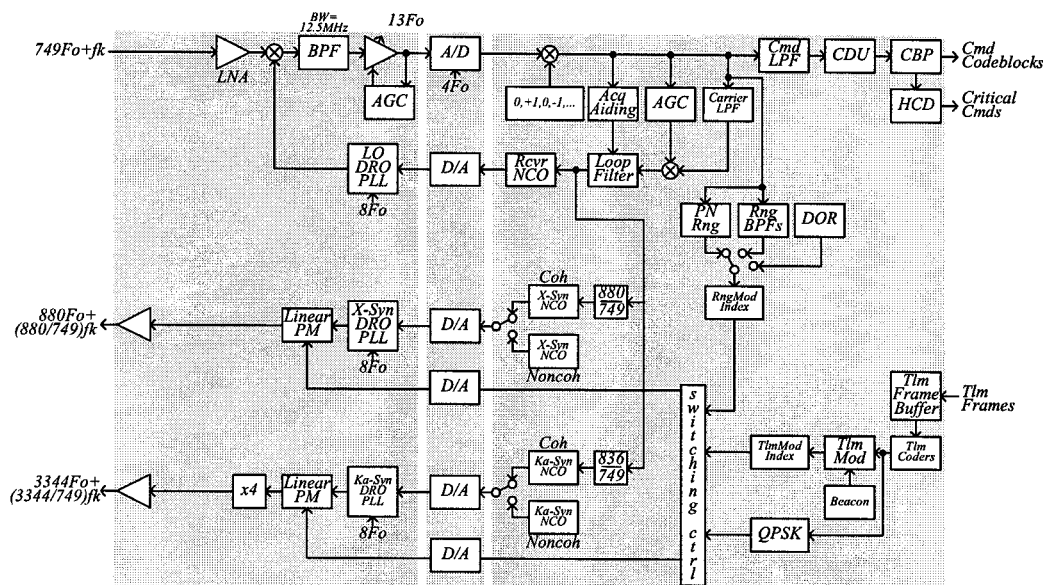


Figure 1. STM Functional Block Diagram

The STM tracks an X-band uplink signal and provides both X-band and Ka-band downlink signals, either coherent or non-coherent with the uplink signal.

The command detector is integrated into the STM that decodes the uplink commands. The maximum uplink command data rate is 2000 bits per second (bps). The STM implements also a codeblock processor and a hardware command decoder.

Downlink telemetry is received from the spacecraft CDS as telemetry frames. The STM provides the following downlink telemetry coding options: 1) Reed-Solomon coding with interleave depths of one and five, 2) the standard convolutional coding with rates (7-1/2) and (15-1/6) used in the Deep Space Network (DSN), and 3) Turbo coding with rates 1/3 and 1/6. The downlink symbol rates can be linearly ramped to match the G/T curve of the receiving station, providing up to a 1.9 dB increase in data return. Data rates range from 5 bps to 24 Mbps. The STM provides three telemetry modulation modes: 1) modulated subcarrier, 2) biphasic-L modulated direct on carrier, and 3) Offset-QPSK.

The STM provides also the capability to generate one of four telemetry beacon tones that are not harmonically related.

The STM provides three ranging modes: 1) standard turn around ranging, 2) regenerative pseudo-noise (PN) rang-

ing, and 3) differential one-way ranging (DOR) tone. The regenerative PN-ranging provides the capability of increasing the ground received ranging signal-to-noise ratio (SNR) by up to 30 dB.

The STM provides two different avionics interfaces to the CDS data-bus: 1) MIL STD 1553B bus and 2) industry standard PCI interface. Digital interfaces provide the capability to switch between high gain and low gain antennas and to point Ka-band antennas in future missions.

Linear Phase Modulator Design Specifications

The design specifications for the 8.4-GHz analog phase modulator are given in Table 1.

Table 1. Linear Phase Modulator Specifications

Parameter	Value
RF Frequency Range	8 GHz - 8.5 GHz
Total Phase Shift	± 140 deg.
Modulation Linearity	$\pm 8\%$
over ± 140 deg.	
Modulation Bandwidth	> 100 MHz
Modulation Sensitivity	> 120 deg/V
Insertion Loss	< 8 dB
Insertion Loss Flatness	± 0.5 dB

The analog phase modulator must be capable of large linear phase deviation, low loss, and wideband operation with good thermal stability. In addition, the phase modulator and its driver circuit must be compact and consume

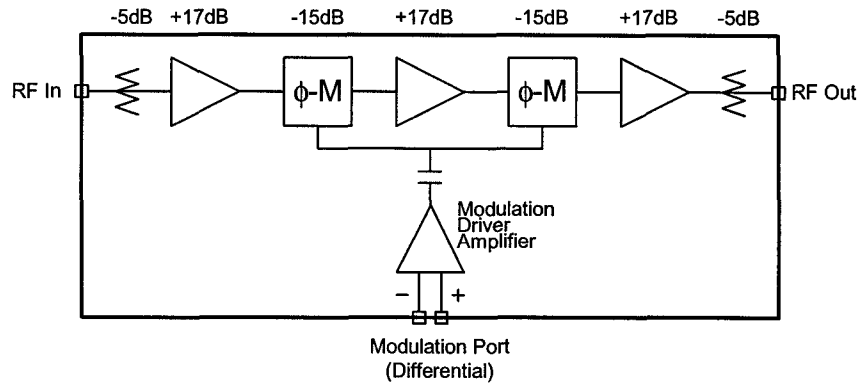


Figure 2. X-Band Linear Phase Modulator Block Diagram

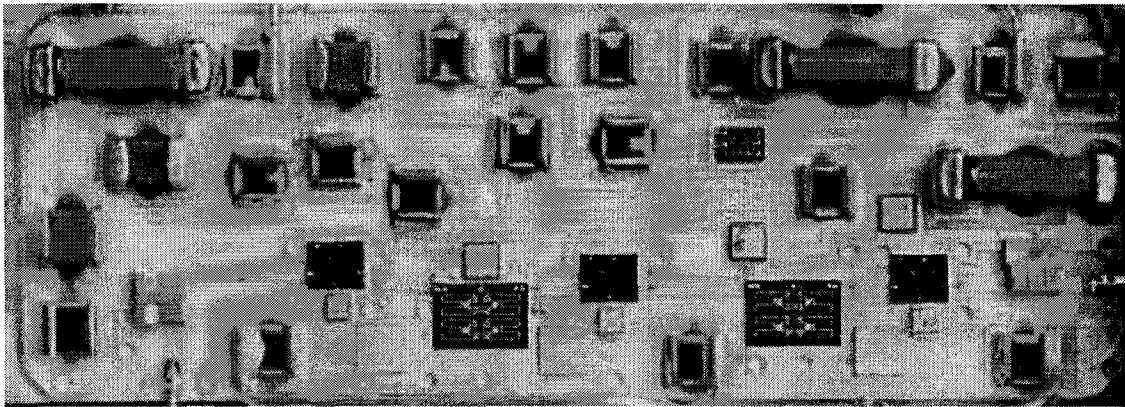


Figure 3. X-Band Linear Phase Modulator Picture

low dc power. The design is to provide ± 140 degrees of peak phase deviation to accommodate downlink modulation of telemetry and ranging signals. The tolerance on the phase deviation linearity is $\pm 8\%$. The insertion loss should be less than 8 dB and its variation with phase shift should be within ± 0.5 dB. The phase delay variation specifications over the transponder hardware qualification environment, -30°C to $+85^\circ\text{C}$, is less than 0.5 ps/ $^\circ\text{C}$ for the phase modulator. The design approach utilizes custom designed GaAs MMIC phase modulators to provide low loss and well-controlled phase performance.

The organization of the article is as follows. The description of the hybrid modulator circuit configuration is presented in Section 2. The test data and analysis are presented in Section 3. The conclusions are presented in Section 4.

2. DESCRIPTION OF THE LINEAR PHASE MODULATOR

The block diagram schematic of the hybrid X-band linear phase modulator is shown in Figure 2. The modulator photograph is shown in Figure 3. It is designed as a drop-in circuit on a 25-mil thick alumina substrate into the transponder X-band exciter module. It consists of two MMIC phase modulators and three MMIC amplifiers, and a driver op-amp integrated circuit. The modulator measures about $10\text{ mm} \times 30\text{ mm}$.

Description of the MMIC Linear Phase Shifter

The MMIC linear phase shifters were developed by Hittite Microwave Co., under contract with the NASA Small Business Innovation Research (SBIR) program.

The MMIC phase-shifter chip incorporates a four-stage reflection phase shifters with Lange couplers and MESFET-varactors to provide a phase deviation of ± 100 degrees with better than 8 % linearity. The MESFET used in this application is a standard 0.5-micron depletion mode MESFET from Triquint (HA2) analog MMIC process. This linear phase shifter has been simulated using CAD tools to have 300 degrees of continuous phase shift in the 8.4 GHz to 8.6 GHz range with the variation of the MESFET-varactor control voltage from 1 V to 9 V. Two design and fabrication iterations were used to optimize the performance of the phase-shifter chips. The chip performance is given in Table 2.

Table 2. MMIC Linear Phase-Shifter Chip Performance

Parameter	Value
Chip Size	1.5mm \times 2.2mm \times 0.1mm
RF Frequency Range	8 GHz - 8.5 GHz
Measured at Frequencies	8 GHz, and 8.4 GHz
Total Phase Shift (2.5 V to 8.5 V)	216 deg
Modulation Linearity over ± 50 deg	± 4.8 %
Modulation Linearity over ± 100 deg	± 7.8 %
Modulation Bandwidth	350 MHz
Modulation Sensitivity	36 deg/V
Insertion Loss	- 14.7 dB
Insertion Loss Flatness	± 0.8 dB
RF Port Return Loss	- 18 dB

For the X-band downlink, to satisfy the phase-deviation requirement of greater than ± 140 degrees, the 8.4-GHz phase modulator includes two phase-shifter chips in the design.

For the Ka-band downlink, the phase modulator is followed by a times-4 circuit as shown in Figure 1. This arrangement reduces the phase-deviation requirement of the phase modulator to ± 35 degrees. Therefore, the 8-GHz phase modulator uses only one phase shifter in the design.

The overall phase sensitivity from the modulating port to the RF port of greater than 120 degrees/V is met by adjusting the gain of the driver amplifier for both the 8.4-GHz and the 8-GHz phase modulators.

3. MEASURED RESULTS

3.1) 8.4-GHz Phase Modulator Test Results

The test results for the X-band phase modulator are presented below. In these tests, we by-passed the driver amplifier and applied the modulating signal directly to the phase shifters. This enabled us to vary the d.c. bias volt-

age and obtain the characteristics of the phase modulator without the driving amplifier. The gain of the driving amplifier is adjusted later to satisfy the overall phase modulation sensitivity requirement.

In these characterization tests, we used 82-degree and 138-degree modulation index levels, which are easily identified from the output frequency spectrum. For a sinusoidal modulating signal, the 82-degree modulation index is obtained when the carrier power equals the first sideband power ($J_0/J_1 = 0$ dB) and the 138-degree modulation index is obtained when the carrier power attains its first minimum.

Modulation Signal Level

In this test, a sinusoidal modulating signal of frequency 1 MHz is used. The modulation signal amplitude (A_1) for 82-degree modulation index and the modulation signal amplitude (A_2) for 138-degree modulation index are shown in Figure 4. The maximum carrier suppression measured vs. d.c. bias voltage is greater than 20 dB over the temperature range from -45°C to $+75^\circ\text{C}$.

Modulator A.C. Sensitivity

The average modulator sensitivity over ± 82 -degree-range is determined by using the formula $\mu_1 = 82/A_1$ deg/V, and over ± 138 -degree-range by using the formula $\mu_2 = 138/A_2$ deg/V.

For the d.c. bias voltage of + 4 V, the modulator sensitivity is about 68 deg/V at room temperature. The a.c. sensitivity varies from 64 deg/V to 69 deg/V over the temperature range from -45°C to $+75^\circ\text{C}$.

Modulator A.C. Linearity

The modulator linearity is obtained from the two modulator sensitivity measurements as $(\mu_2 - \mu_1)/\mu_1$. The modulator linearity results are shown in Figure 5.

For the d.c. bias voltage of + 4V, the modulator nonlinearity is less than 9% over the temperature range from -45°C to $+75^\circ\text{C}$.

Modulator A.C. Phase Shift Curves

The modulator a.c. phase shift curves are obtained by integrating the modulator sensitivity curves. The modulator a.c. phase shift curves are shown in Figure 6. This figure shows the overall linearity of the phase shift characteristic of the phase modulator over the d.c. bias voltage range from + 2 V to + 5.5 V.

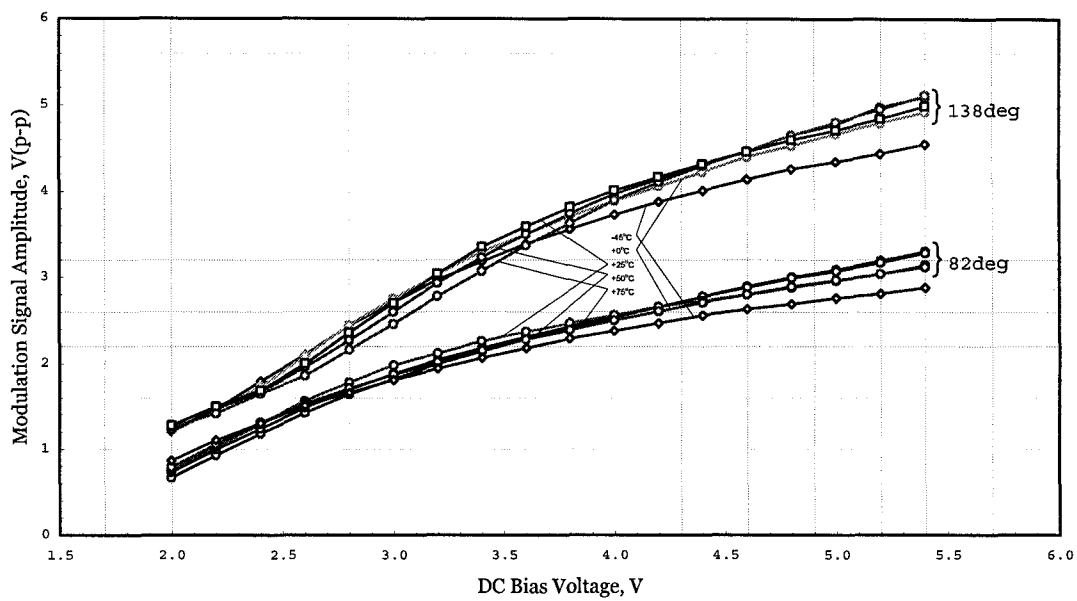


Figure 4. Modulation Signal Levels for 82-deg and 138-deg Mod Indices

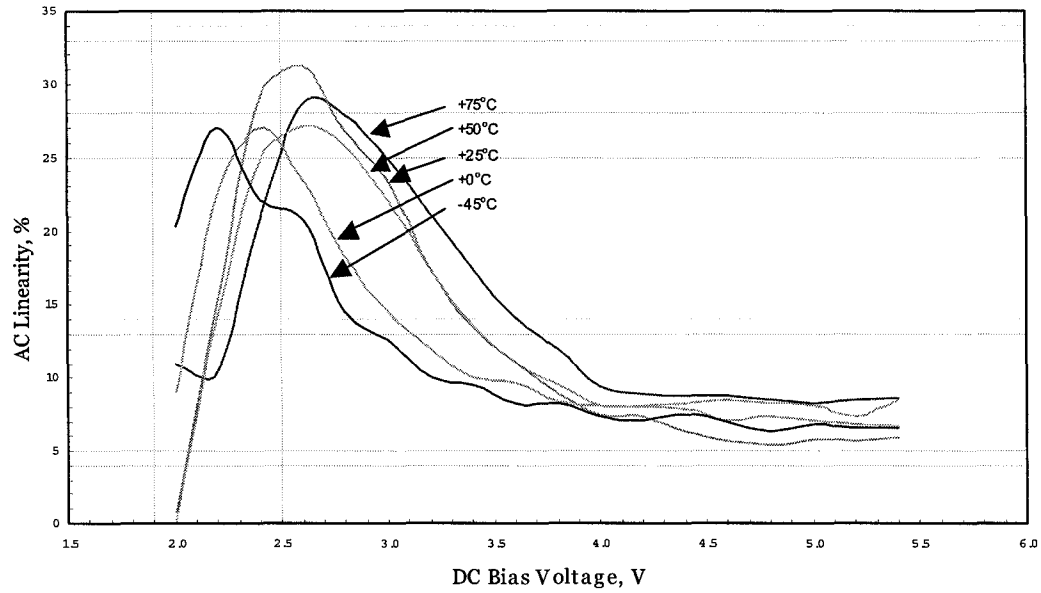


Figure 5. Phase Modulator A.C. Linearity

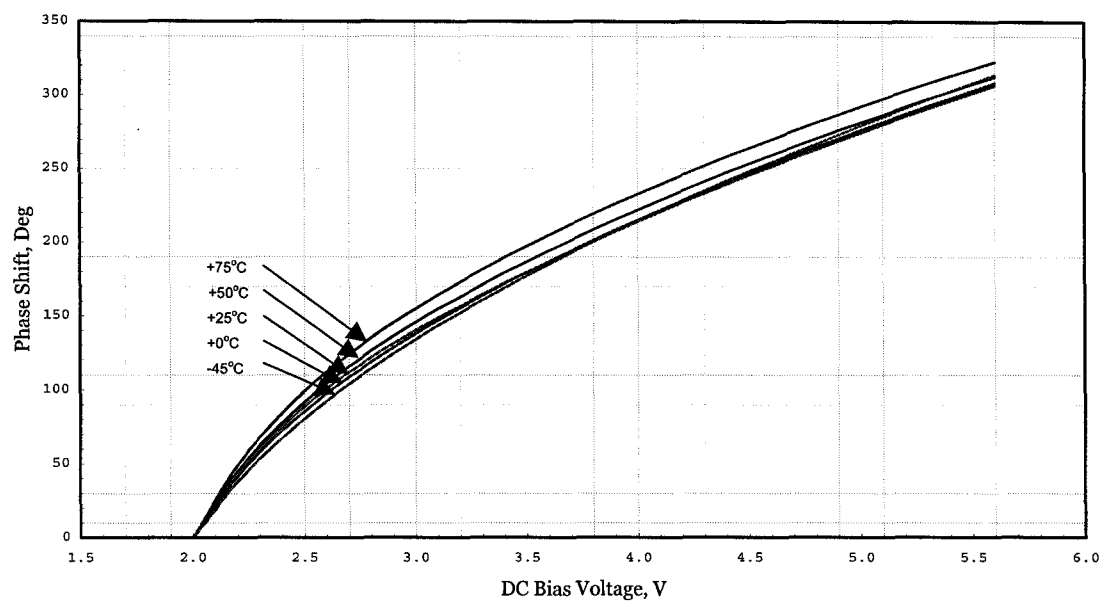


Figure 6. A.C. Phase Shift Curves for the Phase Modulator

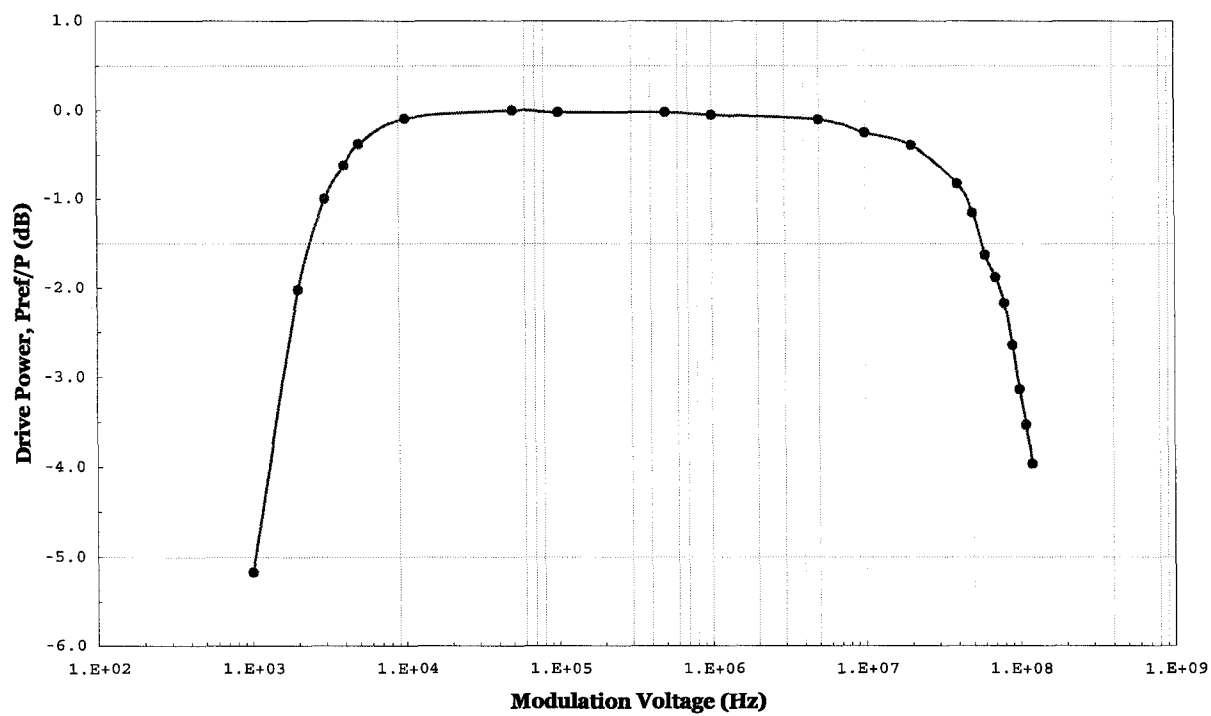


Figure 7. Modulating Bandwidth for the Phase Modulator

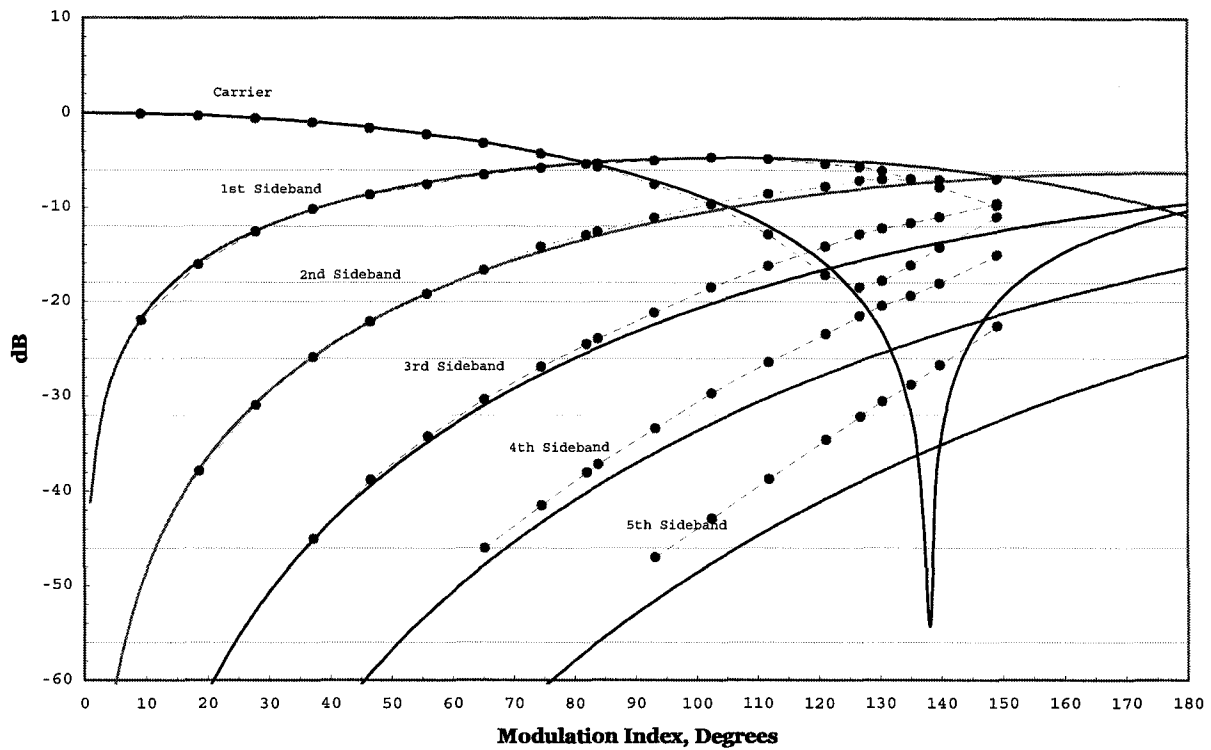


Figure 8. Phase Modulation Sideband Power Levels vs. Phase Mod Index

Modulator Output Power Variation

The r.f. output power variation versus the d.c. bias voltage is measured at different temperatures. For the dc bias voltage of +4 V, the output power varies from -6 dBm to +1.5 dBm over the temperature range from -45°C to +75°C. The phase modulator output drives another amplifier that is operated in the saturation region, which reduces the output power variation to less than 1 dB.

Modulation Bandwidth

The modulation bandwidth is obtained at the d.c. bias voltage of +4 V by changing the frequency of the modulating signal and measuring its amplitude and power for a modulation index of 82 degrees ($J_0/J_1 = 0$ dB). In order to obtain a frequency transfer function similar to filters, we plot the relative signal power level, P_{ref}/P versus the frequency, where P is the modulating signal power and P_{ref} is the reference power level. The P_{ref} is chosen as the measured power of the modulating sinusoidal signal of frequency 100 kHz. The result is shown in Figure 7. The modulation bandwidth is about 100 MHz.

Modulation Sidebands

The phase modulation sideband power levels are measured by applying a 100-kHz sinusoidal modulating signal and varying its amplitude. The amplitude data of the modulating signal is converted to modulation index level by multiplying the amplitude by the modulator sensitivity over ± 82 degrees. The results are shown in Figure 8. The measured sideband power levels match very well with the theoretical levels for modulation indices less than 82 degrees and gradually deviate from them for modulation indices greater than 82 degrees.

3.2) 8-GHz Phase Modulator Test Results

We tested the 8-GHz phase modulator by applying the modulating signal directly to the phase shifter and varying the d.c. bias voltage. The gain of the driving amplifier is adjusted later to satisfy the overall phase modulation sensitivity requirement.

In these tests, we used 56-degree and 82-degree modulation index levels, which are easily identified from the output frequency spectrum. For a sinusoidal modulating

signal, 56-degree modulation index is obtained when the carrier power is 5-dB above the first sideband power ($J_0/J_1 = 5$ dB), and the 82-degree modulation index is obtained when the carrier power equals the first sideband power ($J_0/J_1 = 0$ dB).

The test results for the Ka-band phase modulator are similar to the X-band phase modulator. For the d.c. bias voltage of +4 V, the modulator sensitivity is about 42 deg/V at room temperature and varies from 40 deg/V to 54 deg/V over the temperature range from -45°C to $+75^\circ\text{C}$. The modulator linearity over ± 56 degrees is less than 4 %. The modulating bandwidth is greater than 100 MHz.

4. CONCLUSIONS

The linear phase modulator designs presented are used in the STM to phase modulate the X-band and Ka-band downlink frequencies. The linear phase modulator design used custom developed MMIC phase shifter chips. The important requirements of ± 140 -degree phase deviation, less than 8 % phase linearity, and greater than 100-MHz modulation bandwidth are met. The excellent linearity reduced the intermodulation loss when a telemetry and a ranging signal applied to the phase modulator simultaneously.

The drop-in phase modulator circuits are implemented on separate substrates, which enabled us to test and adjust the gains of the driver amplifiers separately. Their small size made it possible to reduce the size of the synthesizer modules.

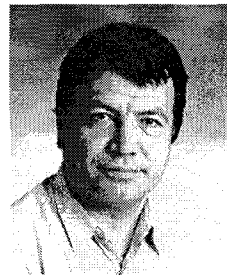
In the future, we are planning to integrate the phase shifters, the amplifiers, and the driver circuits in an r.f. integrated circuit.

5. ACKNOWLEDGEMENT

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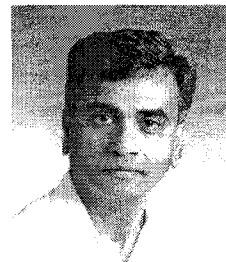
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